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This research consisted of studies of the fundamentals and applications of long Josephson Junctions and very small junctions, all fabricated out of NbN. We have developed technology for fabricating by reactive sputtering high quality long Josephson junctions with current densities of 100-1,000 A/cm^2. Such junctions were used for studies of giant steps on the I-V curve caused by fluxon pinning and of macroscopic quantum tunneling down to 15 mK. A new system, a long Josephson junicition biased at Fiske steps, is presented for studies of Macroscopic Quantum Tunneling. Our results show applications of fluxons in long Josephson junctions for Fluxon Oscillator, Voltage Standard, and for observing Macroscopic Coherent Tunneling. We have also studied very small NbN junctions fabricated with a STM where single electron tunneling is observed. We were the first to present such tunneling at room temperature; this is important for applications. Students and postdoctoral fellows were involved in this research.

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FINAL REPORT

HIGH FREQUENCY BEHAVIOR OF LONG AND SMALL JUNCTIONS

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ABSTRACT

This research consisted of studies of the fundamentals and applications of long Josephson Junctions and very small junctions, all fabricated out of NbN. We have developed technology for fabricating by reactive sputtering high quality long Josephson junctions with current densities of 100-1,000 A/cm^2. Such junctions were used for studies of giant steps on the I-V curve caused by fluxon pinning and of macroscopic quantum tunneling down to 15 mK. A new system, a long Josephson junction biased at Fiske steps, is presented for studies of Macroscopic Quantum Tunneling. Our results show applications of fluxons in long Josephson junctions for Fluxon Oscillator, Voltage Standard, and for observing Macroscopic Coherent Tunneling. We have also studied very small NbN junctions fabricated with a STM where single electron tunneling is observed. We were the first to present such tunneling at room temperature; this is important for applications. Students and postdoctoral fellows were involved in this research.

I. INTRODUCTION

This project consisted of studies dealing with the fundamental aspects and applications of two types of junctions: long Josephson junctions exhibiting fluxon dynamics and very small junctions demonstrating single electron tunneling behavior. The junctions were fabricated out of NbN, a material important for superconducting electronics and devices. The goals were: basic research in the physics of these devices and exploration of possible applications of such devices. The results presented here deal with both aspects.

A Josephson junction is long when one of its dimensions, L, is larger than a characteristic penetration depth, the Josephson penetration depth λ_j. In that case the junction when suitably biased can support fluxon motion whose dynamics display a variety of high speed phenomena. The penetration depth λ_j depends on the critical current density J_c of the junction and it is given by:

$$\lambda_J = (1/\mu_o \, dJ_c)^{1/2} \quad (\phi_o/2\pi) \tag{1}$$

where d is the magnetic thickness of the barrier ($2\lambda_L + t$) with λ_L being the London penetration depths and ϕ_o the flux quantum. The penetration depth λ_J is to a Josephson junction as what the London penetration depth λ_L is to a bulk superconductor. When a magnetic field is applied to this type of junction there will be induced shielding currents which flow within a distance $\sim \lambda_J$ from the edge of the barrier; when this field exceeds a critical value H_{c1J}, Josephson fluxons enter the junction from one of the edges. When the junction is biased with a current, a Lorentz force is exerted on the fluxons causing them to move within the junction as if it were a transmission line; this leads to interesting fluxon dynamics. A manifestation of such effects are constant voltage current steps in the presence of a magnetic field; they are known as Fiske steps. Because such junctions are difficult to fabricate, they have not been studied as much as the regular junctions. Interesting applications are the flux-flow transistor, a 3-terminal device, and the high frequency oscillators based on fluxon reflections at the ends of the junction.

In the other extreme, a very small junction will exhibit single electron tunneling when the electrostatic energy of a single electron is larger than the thermal energy; thermal fluctuations will be suppressed when:

$$e^2/2C > kT \tag{2}$$

Since the charge of a single electron is fixed, it is clear from the above equation that the junction capacitance C has to be extremely small and probably the temperature T should be low. Quantum fluctuations must also be suppressed and this will occur when the junction conductance is:

$$G > 1/R_Q \tag{3}$$

where R_Q is the quantum of resistance, $4e^2/h$. In this work we have used STM - formed junctions. The studies presented here have been possible because we have:

- a ^3He - ^4He dilution refrigerator
- thin film facilities with 2 magnetron sputtering systems.

When conditions given by equations 2 and 3 are met, the I-V curve of such a junction will show a Coulomb blockade; the tunneling current increases when the voltage exceeds the Coulomb gap voltage e/2c. There is another manifestations of this effect; it occurs when there is a double junction in series and in that case the I-V curve shows characteristic steps, known as the Coulomb staircase. The tunneling of electrons, as singles or pairs (in superconductors), leads to the emissions of microwaves. We were interested in studying this radiation using the long Josephson junction oscillators. That is the connection between the two parts of this project.

II. ACHIEVEMENTS

A. LONG JOSEPHSON JUNCTIONS

- NbN Technology

All the research presented in this report has been based on NbN devices. The long Josephson junctions and the very small junctions were fabricated from sputtered NbN films. They were formed reactively during the sputtering with magnetron guns.

In fabricating the long Josephson junctions first a sandwich on a doped silicon substrate was formed with 3000Å of NbN covered immediately with ~ 10-20Å of magnesium. Thermal oxidation formed MgO which is the barrier in our junctions. At that point following the oxidation, another layer of 3000Å of NbN was deposited without breaking the vacuum. Junctions were formed using photolithography and mashs which were computer-generated. Because the coherence length is very short in NbN, i.e. $\xi \sim 40$Å, and because the junctions are long, 100μm and 6μm wide, there were difficulties in fabricating suitable junctions; shorts and non-uniform current distributions were common problems. With tight control on the fabrication procedure we succeeded in fabricating junctions with $T_c \sim 17$K and critical current densities of 100 - 1,000 A/cm^2. To ensure that the current distribution in the junction was uniform, the top and bottom electrodes had 8 current injection fingers per electrode. Fig. 1 shows a typical long Josephson junction. Junctions characteristics showed an energy gap 2Δ of 5 mV at 4.2K. Once our process was developed we could produce routinely high quality long Josephson junctions, suitable for studies of fluxon dynamics.

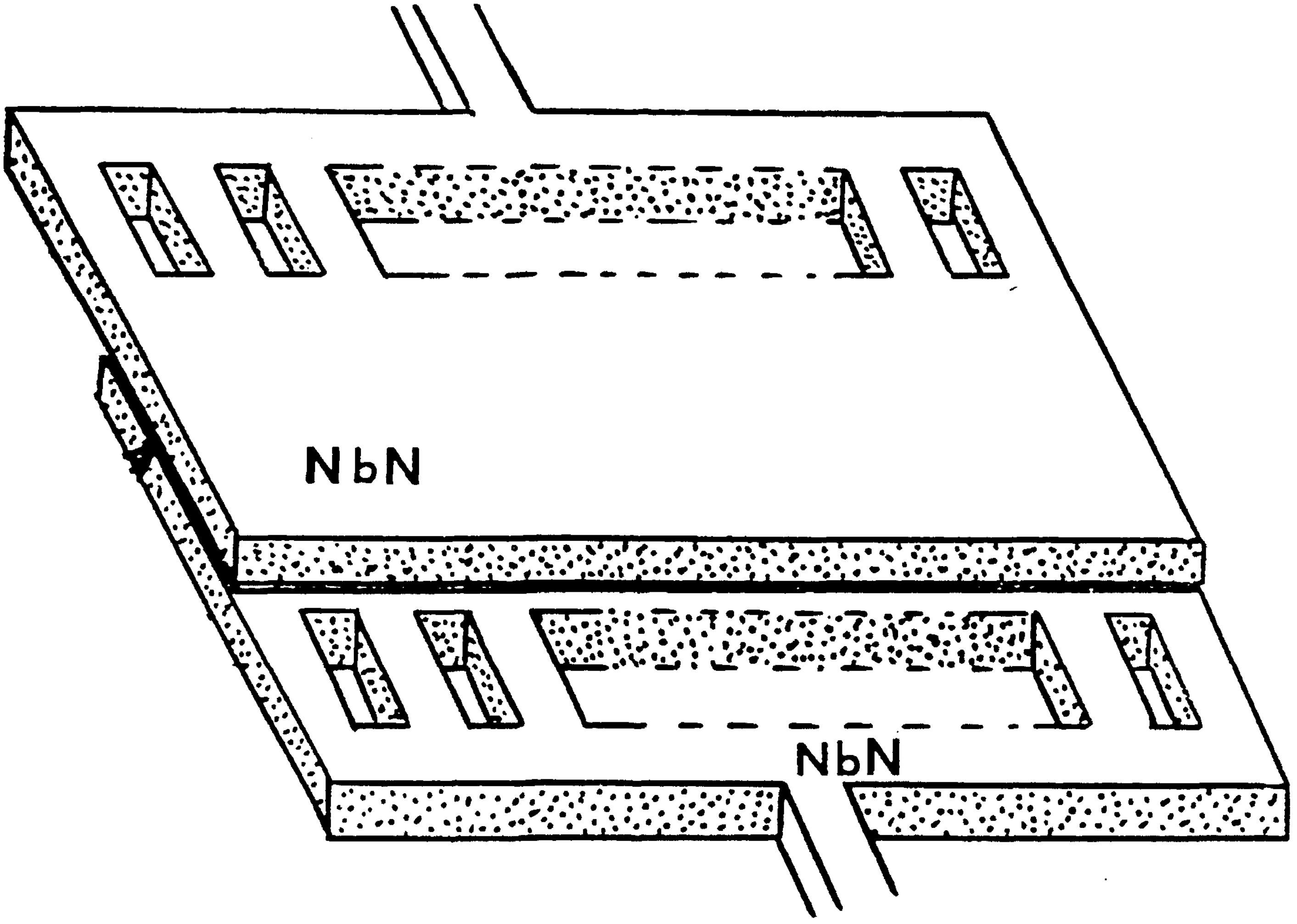


Fig. 1. Long Josephson junction with current injection electrodes.

- Giant Steps in I-V Curves

Studies of the I-V curves of our junctions in magnetic fields showed structure attributed to fluxon dynamics. The structure consisted of steps which are usually called Fiske steps, and they correspond to the various modes of fluxons in a junction. The steps in NbN junctions were different from those observed on earlier junctions of $Nb-Al_2O_3-Nb$. The steps here were very sharp and they did not occur at voltages corresponding to the successive fluxon nodes given by:

$$V_n = \frac{n\bar{c}\phi_o}{2L} \tag{4}$$

where $\bar{c}$ is the fluxon speed in the junction and n is the number of fluxons. We observed that the steps jumped in bunches of n rather than progress successively with each additional fluxon increasing n by 1.

One possibility for this effect was the poor shielding of the electrodes since their thickness of 3000Å was comparable to the London penetration depth. We investigated this by depositing on each electrode Nb which has a much shorter λ_L. Essentially we had $Nb-NbN-MgO_2-NbN-Nb$. This did not change the behavior even though Nb shielded well the junction from the external magnetic field.

Further investigations showed that the large steps were caused by fluxon pinning after they were mucleated at the junction edges. Non-uniformity in current distribution in the junction and defects were responsible for the pinning. Moreover, NbN is quite granular and this can cause problems with flux trapping when the junctions are cooled.

Multiple fluxon transitions at the steps and the sharpness of the steps can be important for device applications. This will be discussed later.

- Macroscopic Quantum Tunneling

This is a topic of current interest and we feel that we have an ideal system for studying this subject. The problem is to observe quantum mechanical effects at the macroscopic level. A system has to be chosen which is relatively simple, whose parameters can be well characterized, and where dissipation can be made quite small. An obvious manifestation of quantum mechanics would be the tunneling of a macroscopic variable and the effects of dissipation. Associated with this is the interesting possibility of observing coherence in the tunneling. Previous studies in this field have used small regular junctions by themselves or incorporated in SQUIDS. We present here a new system for such studies, the long Josephson junction based on the dynamics of fluxons in it. We define the total magnetic flux through our junctions as the macroscopic quantum mechanical

variable. In a magnetic field the Fiske steps correspond to metastable states where the macroscopic variable can tunnel to the adjacent step and back. Biasing the junction with a current between two adjacent steps leads to thermally activated hopping from one state to the next and back in the high temperature region, and tunneling at very low temperatures. Our studies show that both regions occur as the junction is cooled from 4K to 14mK in a ^3He - ^4He dilution refrigerator. Because of dissipation the tunneling is incoherent. Our results also show that by reducing the dissipation (caused by quasiparticles in the barrier and in the electrodes, as well as radiation losses), we have the chance of perhaps seeing coherent tunneling at the macroscopic level; this has never been observed. In fact, our system with two almost degenerate potential wells is the analog of the NH_3 molecule where the N tunnels between its equivalent sites in the molecule. This is shown in Fig. 2 for our system and the NH_3 molecule. One experiment to observe the effect would consist of looking at the spectrum of the emitted radiation in the microwave region from the long junction as the magnetic flux tunnels back and forth between the double well potential.

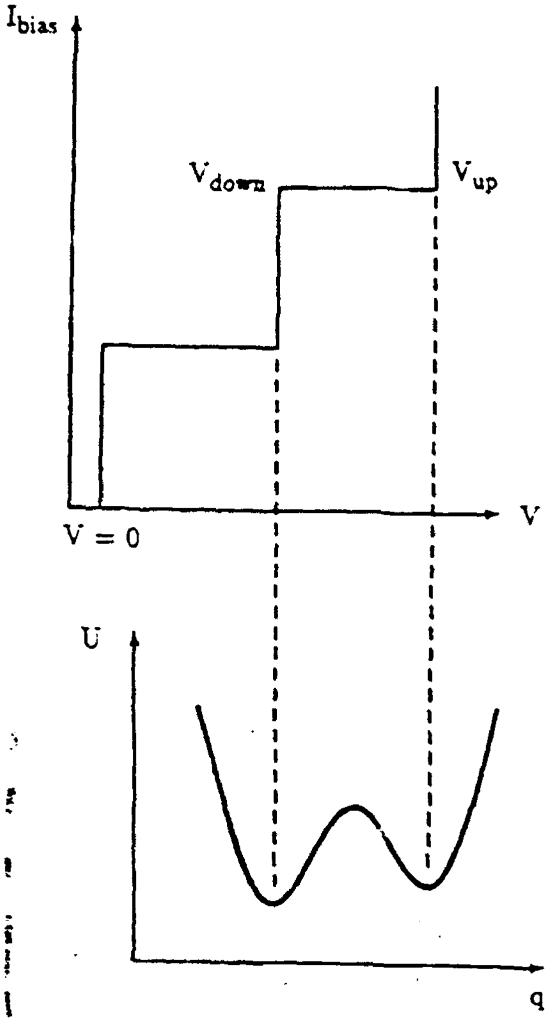
Our results show the temperature dependence of the switching rate in the tunneling. This is presented in Fig. 3. It is consistent with incoherent tunneling in a degenerate double-well system, where the temperature dependence of the switching rate Γ follows the predicted power low, $\Gamma \sim T^{2\alpha c-1}$ with α_c being a dimensionless dissipation parameter. This is to the best of our knowledge the first application of the long Josephson junction to the study of macroscopic quantum tunneling.

- Applications

The long Josephson junction is an interesting system with great potential for all sorts of applications (anything with fluxons which are moving that fast is interesting) which have not been explored much. As a result of the research reported here, we present a few applications of the long Josephson junction.

(i) <u>Fluxon Oscillator</u>

The resonant motion of fluxons in a long Josephson junction, as evidenced by the series of constant voltage current steps, leads to the emission of microwaves from the junction ends. In our results we have large current steps which have interesting features in that they are very sharp. The large steps consist of release of bunches of fluxons which were pinned at the junction edge; subsequently the bunch of fluxons behaves resonantly in the junction due to the Lorentz force of the bias. Very likely the fluxons remain bunched up in their motion in the junction (this has been shown to be possible by simulations and experimental observations). Reflection of a bunch of fluxons causes a higher radiation output. It is equivalent to having an array of junctions to increase the output power level, except that our system is more compact. The output frequency,



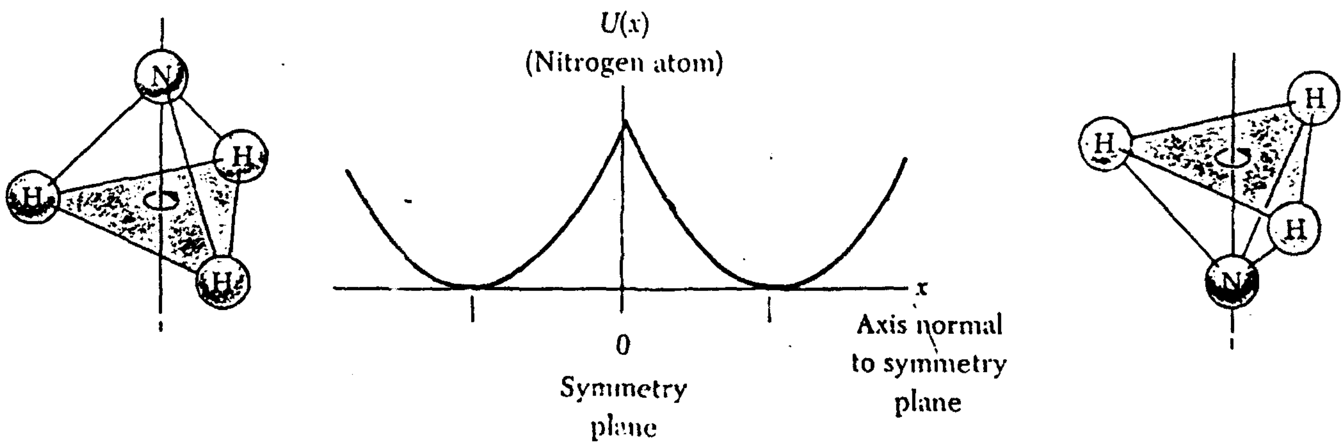


Fig. 2. Double Well for long Josephson junction biased at Fiske steps. Double well for NH_3 molecule.

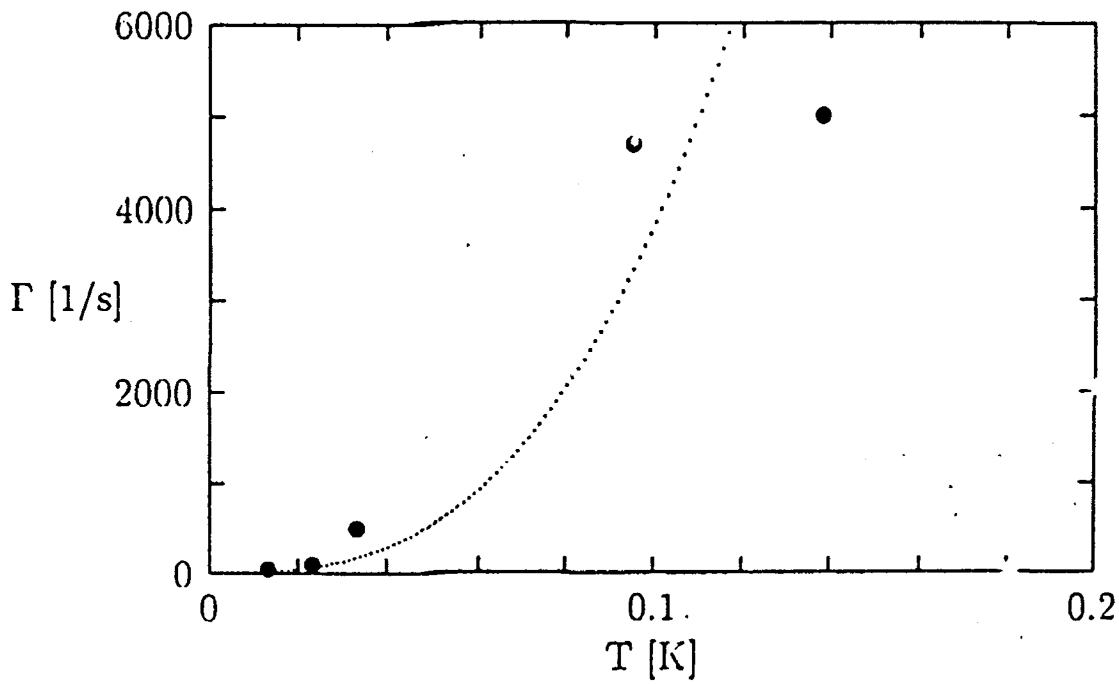


Fig. 3. Switching rate of long Josephson junction as a function of temperature in the incoherent tunneling regime.

linewidth, and power levels of our junction biased at such large steps have to be investigated; the static results appear very promising. Fig. 4 shows a typical set of large steps on the I-V curve.

(ii) Voltage Standard

The standard volt is presently defined by a large series array of hysteretic Josephson junctions synchronized to an external microwave signal. We propose the application of our large steps in the long NbN Josephson junctions (produced by the internal microwaves from fluxon motion) to the definition of a standard volt. Our junctions are only biased by a dc current and an external magnetic field; there is no external microwave drive. Since the steps are very well defined, a few long Josephson junctions could be series-connected to produce a long chain of current steps over a wide range of voltages. It is a dc application whose main importance is its simplicity and perhaps better performance over the present ones which utilize external high frequency synchronization.

(iii) System for Observing Macroscopic Coherent Tunneling

Our studies of tunneling of the magnetic flux through a long Josephson junction has provided the framework for a new set of experiments which could provide the first observation of coherence in tunneling of a macroscopic system. To be in such a position, it is necessary to reduce the dissipation in the junction, i.e. the dissipation parameter α_c must be less than 1. This parameter represents quasiparticle damping in the barrier, surface losses in the electrodes, and radiation losses. The detection of coherence will be difficult since only an indirect measurement can be made. The study of the radiation spectrum as observed by a detector junction close to the long Josephson junction may provide information on the coherence of the system.

B. VERY SMALL JUNCTIONS: SINGLE ELECTRON TUNNELING

In order to fabricate a very small junction which would satisfy Eq. 2, we have used the scanning tunneling microscope (STM) approach. A piezoelectric tube is used to position one electrode of the capacitor relative to the other electrode and thus form the small junction. The fine voltage control of the displacement of one electrode makes it ideal for this experiment. With such a set-up we have investigated its performance at 4.2K. Having established its behavior we have extended studies of single electron tunneling to room temperature.

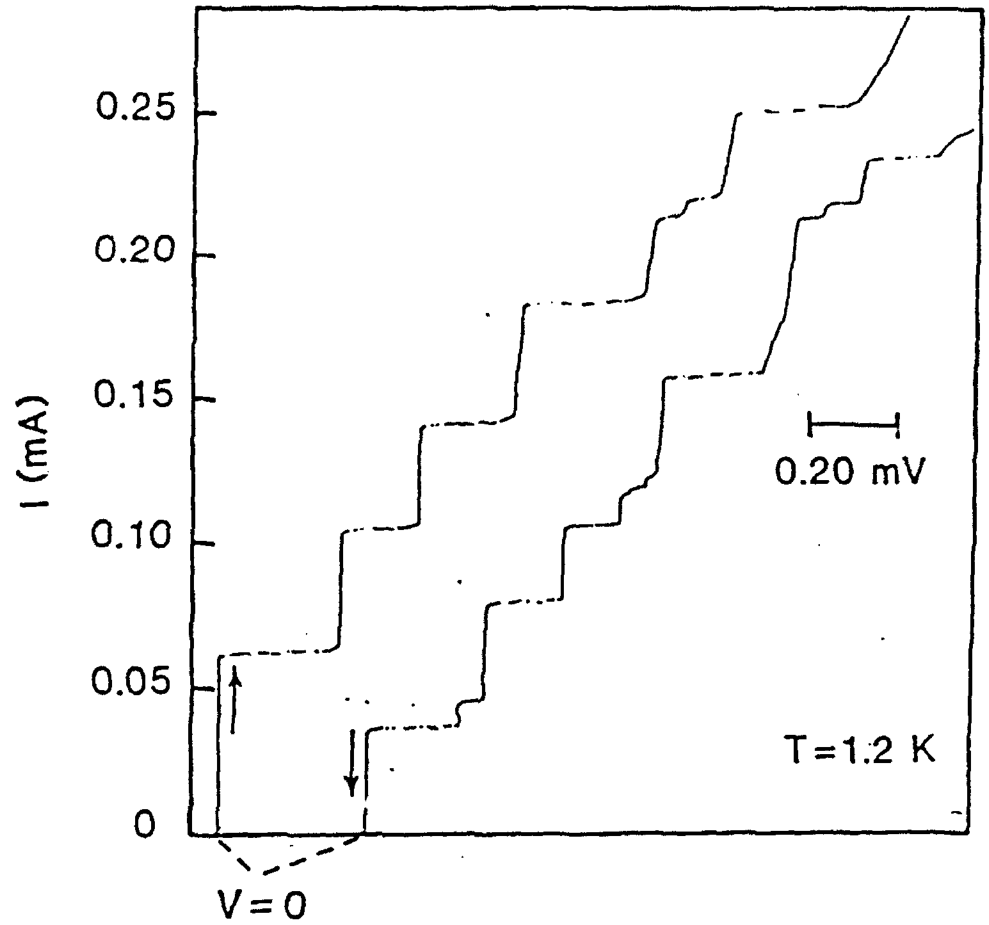


Fig. 4. Large steps on I-V curve of long Josephson junction biased in a small magnetic field.

- Low Temperatures

The goal here was to study the performance of our device in a well-investigated temperature regime, 4.2K. The electrodes consisted of a NbN film, 6000 Å, sputtered on a silicon wafer and a NbN sputtered Nb tip. The reason for using NbN was that we were interested in its characteristics, especially for studies described above. We were able to observe at 4.2K the energy gap of NbN, which was 5.0 Mv. This confirmed the high quality of our thin films. Then we looked for single electron tunneling by changing the spacing between electrodes. Again at 4.2K, we observed the Coulomb blockade and the Coulomb staircase. In order to observe the staircase it is necessary to have a series connected double junction. Such an arrangement was formed in our case by the presence of a very fine particle between the tip and substrate electrodes. This is shown in Fig. 5. The formation of a small particle is promoted by the granularity of the NbN. Analysis of our data points to one capacitor being ~ 2.5 aF while the other onc is ~ 2.0 Af. Some of our results yielded capacitances as low as 0.5-1.0 aF and this led us to repeat the experiments at room temperature.

- Room Temperature

At 300K, a capacitance of 1 aF corresponds to 3.1 kT so the effects should still be observable although the thermal rounding of the steps will be large. The Coulomb blockade and staircase were indeed clearly observable, but with the expected thermal smearing. Room temperature presents other problems associated with the increased voltage noise, thermally - induced vibrations, and so on. Best fits to the data at room temperature give one capacitance of 0.55 aF and the other one of 1.2 aF. One feature not present in the low temperature curves is the increasing conductance with voltage. This can be attributed to a barrier effect or to changes in the density of states in the tip or particle. In an attempt to determine the size of the conducting grains forming the inner electrode of these systems, Atomic Force Micrograph (AFM) were taken of the NbN surface. The results revealed features of about 100Å radius, the heights of these objects ascended up to 80Å. Smaller features could not be resolved but could very well exist. This is consistent with the granularity of NbN which can be in the range 50 to 100Å.

We made various experiments to verify our observations. They have produced evidence that indeed we have observed single electron tunneling at room temperature. This is shown in Fig. 6. We were the first to demonstrate this. Our results open the way for a variety of room temperature experiments where quantum effects can be observed. Also, our experiments make the applications of such devices more attractive since cryogenic temperatures are not needed. We feel that this will be an area which will grow to become an important field, especially for high speed applications.

Recent studies on this system of fluctuations at the steps in the I-V curve further support our claims of observing single electron effects.

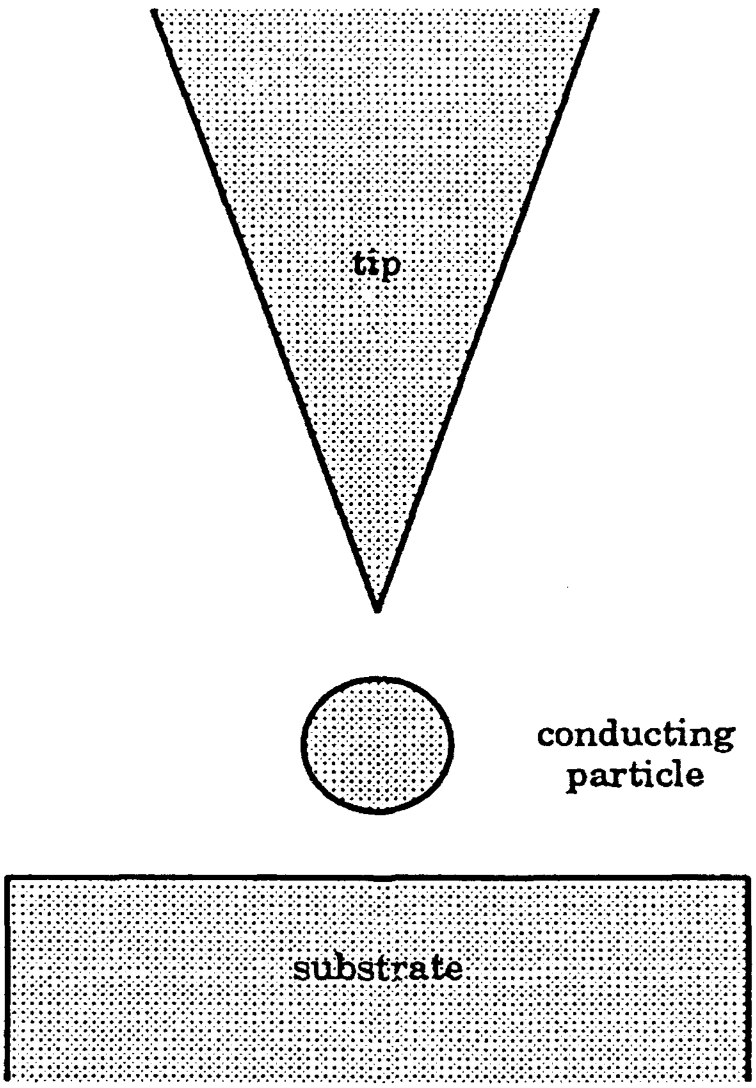


Fig. 5. Schematic of a physical realization of the double junction system using NbN.

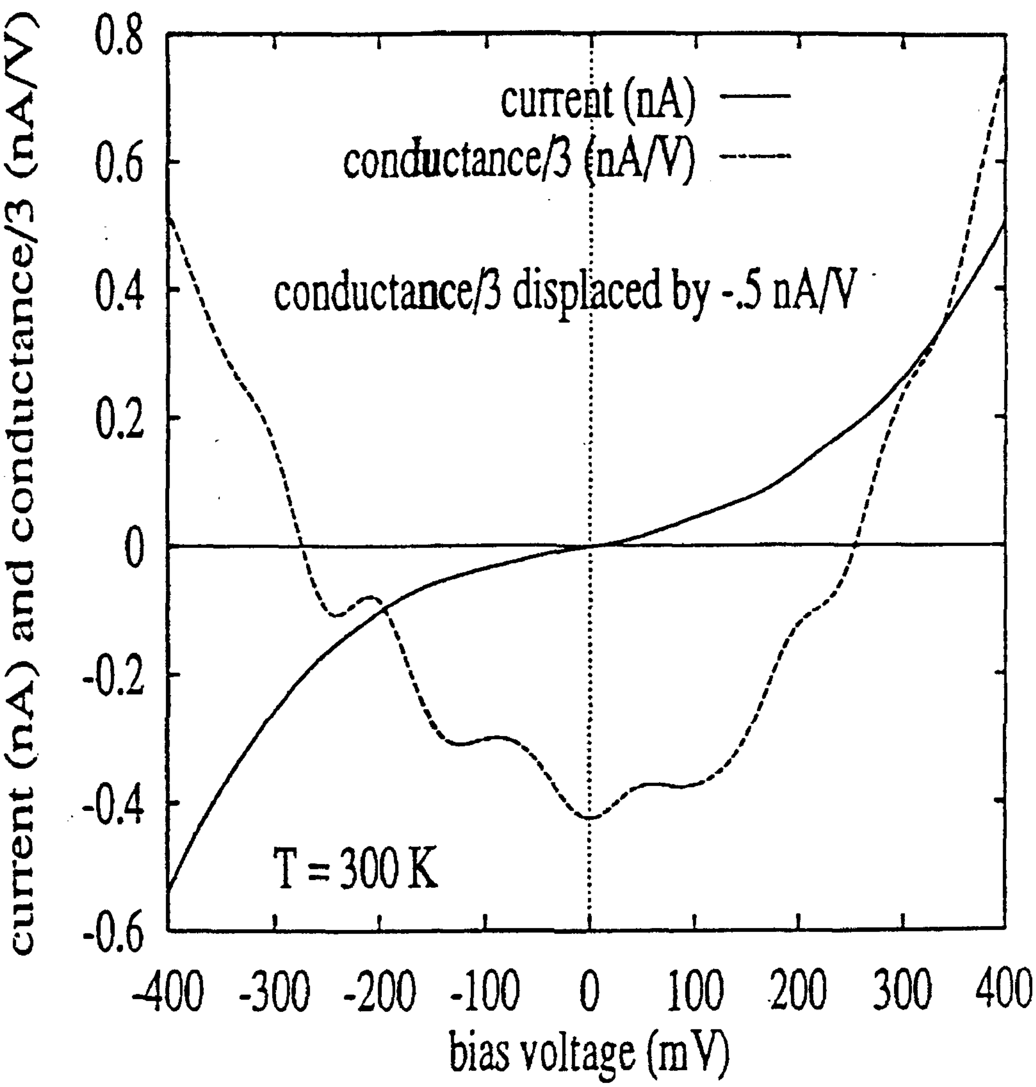


Fig. 6. Room temperature observation of Coulomb blockade and Coulomb staircase using NbN system.

III. CONFERENCE PRESENTATIONS AND PUBLICATIONS

CONFERENCE PRESENTATIONS:

- "Josephson Junction Noise Measurements Using a SQUID Magnetometer", (L. Baselgia-Stahel, O. G. Symko, W. J. Yeh and D. J. Zheng), APS St. Louis, March 1989.

- "Chaos in Long Josephson Junctions Without External RF Drive", (W. J. Yeh, O. G. Symko and D. J. Zheng), APS St. Louis, March 1989.

- "Substeps in the First Fiske Step Mode of Long Josephson Junctions", (W. J. Yeh, O. G. Symko and D. J. Zheng), APS Anaheim, March 1990.

- "Fluctuations in Fluxon Transitions in a Long Josephson Junction at Very Low Temperatures", (L. Baselgia-Stahel, O. G. Symko, W. J. Yeh, D. J. Zheng and M. A. Novak), APS Anaheim, March 1990.

- "Experimental Considerations for Observing Single-Electron Tunneling at Room Temperature" (M. D. Reeve, O. G. Symko and X. Liang), APS Seattle, March 1993.

- "Cooling Below 1K a Long Josephson Junction in the Voltage State", (L. Baselgia-Stahel, O. G. Symko, *D. J. Zheng*), *submitted* LT 20, Oregon.

PUBLICATIONS:

- "Noise Characteristics and Instabilities of Long Josephson Junctions", (B. S. Han, B. Lee, O. G. Symko, W. Yeh and D. J. Zheng), IEEE Trans. Mag. MAG-25, 1396 (1989).

- "Period Doubling in a Perturbed Sine - Gordon System, a Long Josephson Junction" (W.J. Yeh, O.G. Symko and D.J. Zheng), Phys. Lett. A 140, 225 (1989).

- "Chaos in Long Josephson Junctions without External RF Driving Force", (W. J. Yeh, O. G. Symko and D. J. Zheng), Phys. Rev. B42, 4080 (1990).

- "Fluxon Tunneling in Long Josephson Junctions Below 1K", (L. Baselgia-Stahel, O. G. Symko and W. J. Yeh), Physica B. LT-19, III, 575 (1991).

- "Multi-Fluxon Steps in Long Josephson Junctions and Their Application to Oscillators", (L. Baselgia-Stahel, O. G. Symko and W. J. Yeh), IEEE Trans. on Magnetics 27, 3257 (1991).

- **"Macroscopic Quantum Tunneling Between Dynamic States of Long Josephson Junctions"**, (L. Baselgia-Stahel and O. G. Symko), Physics Letters A 166, 399 (1992).

- **"Room Temperature Tunneling Characteristics of Ultra Small Tunnel Junctions"**, (M. D. Reeve, O. G. Symko and R. Li), Modern Phys., Lett. B6, 273 (1992).

- **"Tunneling Studies of Mesoscopic All-NbN Junctions"**, (M. Reeve, O. G. Symko and R. Li), IEEE Trans. on Magnetics, 1993.

- **Large Steps in Long Josephson Junctions"**, (L. Baselgia-Stahel, O. G. Symko and D. J. Zheng), IEEE Trans. on Magnetics, 1993.

- **"Substeps in the First Fiske Step Mode of Long Josephson Junctions"**, (D. J. Zheng, O. G. Symko and W. J. Yeh), submitted to Phys. Lett., 1993.

- **"Fabrication of NbN Long Josephson Junctions"** (M.D. Reeve, O.G. Symko, D.J. Zheng), in preparation

- **"Broad Resonances on Quasiparticle Branch of Long Josephson Junction"** (L. Baselgia-Stahel, and O.G. Symko), in preparation.

IV. PERSONNEL

- **L. Baselgia-Stahel**, graduate student, obtained Ph.D. in June 1992.

- **M. Reeve**, graduate student, will obtain Ph.D. in June 1993.

- **W. J. Yeh**, Research Associate, presently Associate Professor at University of Idaho, Moscow.

- **D. J. Zheng**, Research Associate Professor.

- **R. Li**, graduate student, M. Sc. in June 1990.

- **S. Liang**, graduate student.

- **J. Gold**, undergraduate student.

- **O. G. Symko**, Principal Investigator

V. THESIS

- **"Macroscopic Tunneling in Long Junctions"**, L. Baselgia-Stahel, Ph.D. Thesis, University of Utah, 1992.

- **"Single Electron Tunneling"**, M. D. Reeve, Ph.D. Thesis, University of Utah, 1993.

- **"Low Temperature Scanning Tunneling Microscope and It's Applications to Studies of Small Josephson Junctions"**, R. Li, M. Sc. Thesis, University of Utah, 1990.